Influence of loudspeaker directivity on the measurement uncertainty of the acoustic testing of facades.

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ABSTRACT

One of the most significant aspects of a building's acoustic behavior is the airborne sound insulation of the room façades, since this determines the protection of its inhabitants against environmental noise. For this reason, authorities in most countries have established in their acoustic regulations for buildings the minimum value of sound insulation that must be respected for façades.

In order to verify compliance with legal requirements it is usual to perform acoustic measurements in the finished buildings and then compare the measurement results with the established limits. Since there is always a certain measurement uncertainty, this uncertainty must be calculated and taken into account in order to ensure compliance with specifications.

The most commonly used method for measuring sound insulation on façades is the so-called Global Loudspeaker Method, specified in ISO 140-5:1998. This method uses a loudspeaker placed outside the building as a sound source. The loudspeaker directivity has a significant influence on the measurement results, and these results may change noticeably by choosing different loudspeakers, even though they all fulfill the directivity requirements of ISO 140-5.

This work analyzes the influence of the loudspeaker directivity on the results of façade sound insulation measurement, and determines its contribution to measurement uncertainty. The theoretical analysis is experimentally validated by means of an intermediate precision test according to ISO 5725-3:1994, which compares the values of sound insulation obtained for a façade using various loudspeakers with different directivities.

Keywords: Uncertainty, Façade, Insulation

1. INTRODUCTION

The airborne sound insulation of a building's façades is a very important parameter in urban environments, where environmental noise levels are high. For this reason, the authorities in most countries have established limit values that must be respected for the sound insulation of façades in their regulations on the acoustic performance of buildings [1]. The most common method of verifying compliance with legal requirements is to perform field measurements of sound insulation in the finished buildings. The measurement results are compared with the limits.

Knowledge of the measurement uncertainty is essential to interpret these results. Without a quantitative assessment of measurement uncertainty is impossible to decide whether the test items meet the specifications of the relevant regulatory requirements.

The usual method used to check compliance with legal requirements on airborne sound insulation of façades, is the so called global loudspeaker method described in ISO 140-5:1998 [2]. This method uses a loudspeaker placed outside the building as a sound source. The standard establishes certain requirements for loudspeaker directivity: the directivity of the loudspeaker in a free field must be such that the local differences in the sound pressure level in each frequency band are less than 5 dB, measured on an imaginary surface of the same size and orientation as the test specimen. However, regardless of compliance with coverage requirements, the directivity of the speaker will significantly influence the measurement results and its associated uncertainty.

Numerous papers analyze the measurement uncertainty in sound insulation measurements. Most of these studies refer to measurements of airborne sound insulation between rooms, while some refer to impact sound isolation [3-9]. There are also various references to the measurement uncertainty in the measurement of the sound insulation of façades using road traffic noise [10]. However, there is no specific study in the literature on the measurement uncertainty of the global loudspeaker method.

This paper analyzes the influence of the directivity of the loudspeaker in the measurement result and its contribution to measurement uncertainty.

2. DESCRIPTION OF THE MEASUREMENT METHOD

The quantity specified by ISO 140-5 to express the airborne sound insulation of a façade when using the global loudspeaker method is the Standardized Level Difference ($D_{ls,2m,\ nT}$), defined as:

$$D_{ls,2m,nT} = L_{1,2m} - L_2 + 10\lg(T/T_0) \tag{1}$$

where $L_{1,2m}$ is the outdoor sound pressure 2 m in front of the façade to be tested, L_2 is the space and time averaged sound pressure level in the receiving room, T is the reverberation time in the receiving room and T_0 = 0.5 s.

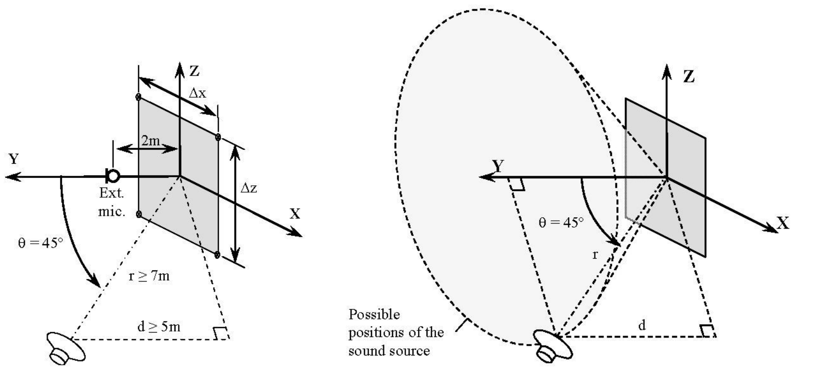


Figure 1– Geometry of the loudspeaker method

The speaker is placed outside the building, at a distance $d \geq 5$ m from the façade, with the angle of sound incidence equal to $(45 \pm 0.5)^{\circ}$, so that the distance from the sound source to the center of the test specimen is $r \geq 7$ m. These conditions are fulfilled for all points belonging to the circumference of the base of a cone with the vertex at the center of the test sample, with the axis normal to it, and whose height and base radius are equal to *d*. Since the loudspeaker is preferably placed on the ground, its position corresponds to the intersection points between the ground plane and the circumference base of the cone, and depends on of the height of the center of the sample. The external microphone is located 2m from the plane of the façade, in the middle. The height of the microphone must be 1.5 m above the floor of the receiving room.

3. INFLUENCE OF SPEAKER DIRECTIVITY ON THE MEASUREMENT RESULTS

3.1 Influence of the directivity of the speaker on the outdoor sound pressure level

The outdoor sound pressure level, $L_{1,2m}$, is affected by the directivity index of the speaker in the direction of the microphone position. The relative position between the sound source and the outdoor microphone varies as a function of the height of the center of the façade. Thus, the angle of incidence to the microphone may vary from one test specimen to another, and with it the effect of loudspeaker directivity on the measured values.

To quantify this effect, measurements were made of the directivity of several types of loudspeakers. For every loudspeaker, the sound pressure level in the outdoor microphone position has been calculated for different possible positions of the speaker. The loudspeakers considered are the most commonly used in acoustical measurements. Table 1 shows the characteristics of the loudspeakers used.

Table 1– Sound sources considered

Source nº	Model	Technical characteristics
1	Coaxial sound source EG-0238	Two-way coaxial speaker (15 "+4")
2	Meyer Sound UPJunior	Two-way speaker (8 "cone + 2" compression driver)
3	Bruel & Kjaer 4224	One-way speaker (12” cone)
4	Bruel & Kjaer 4296	Dodecahedron speaker (twelve 5” cones)

The calculations were performed for a distance from the façade d = 5m, considering only the direct path. Sound source positions considered ranged from the front position to the center of the façade, corresponding to a façade whose center is at a height of 5m, to a lateral position corresponding to a façade whose center is at a height of 1,5 m. For this range of positions, the maximum differences of sound pressure level in the outdoor microphone for each of the sound sources are given in Table 2.

Table 2– Maximum SPL differences at the outdoor microphone position

Freq. [Hz]		100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
	Source 1	0,0	0,0	0,1	0,0	0,4	0,2	0,4	1,2	0,4	0,0	0,4	0,1	0,2	0,6	0,6	0,5	1,5	0,0
Max. Diff.	Source 2	0,4	1,1	0,4	0,2	0,2	0,1	0,3	0,7	1,0	1,1	1,2	0,8	0,8	1,3	3,3	2,2	0,4	2,0
[dB]	Source 3	0,2	0,1	0,1	0,2	0,1	0,1	0,4	0,3	0,6	0,6	0,6	1,3	1,3	1,0	0,5	0,1	2,8	2,4
	Source 4	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,2	0,3	0,4	0,2	1,2	0,4	4,5	3,5	3,0	1,4	9,6

3.2 Influence of the directivity of the speaker on the receiving room sound pressure level

It is not easy to estimate the influence of loudspeaker directivity on the acoustic energy transmitted by the façade. The directivity of the speaker affects the spatial variation of sound pressure levels on the surface of the test specimen. When this variation is large and the façade contains a number of different elements (e.g., the wall itself along with any windows, doors, etc.), there are expected to be variations in sound transmission as a function of the relative position between the maximums of sound pressure level on the surface and the position of the elements of weak insulation.

However, for homogeneous façades, the sound pressure level inside the enclosure seems to depend more on the average value of incident energy over the façade surface than of the spatial variation of such energy. To test this, the acoustic transmission through the façade of a building (4 x 5 x 3.5 m) was simulated by the boundary element method (BEM) using LMS program Sysnoise Rev. 5.5. Material characteristics of the front wall (façade) are 2-cm thick glass. The other walls are considered absolutely rigid.

The different distributions of incident sound pressure on the surface of the façade were calculated separately using EASE 4.3, and entered in the software as input data. The analysis was performed in third octave bands (100 - 2000 Hz), taking into account the coupling between vibrations of the façade and the sound field caused by these vibrations inside the building. The incident pressure distributions in all the cases studied were different and asymmetrical (Fig. 2).

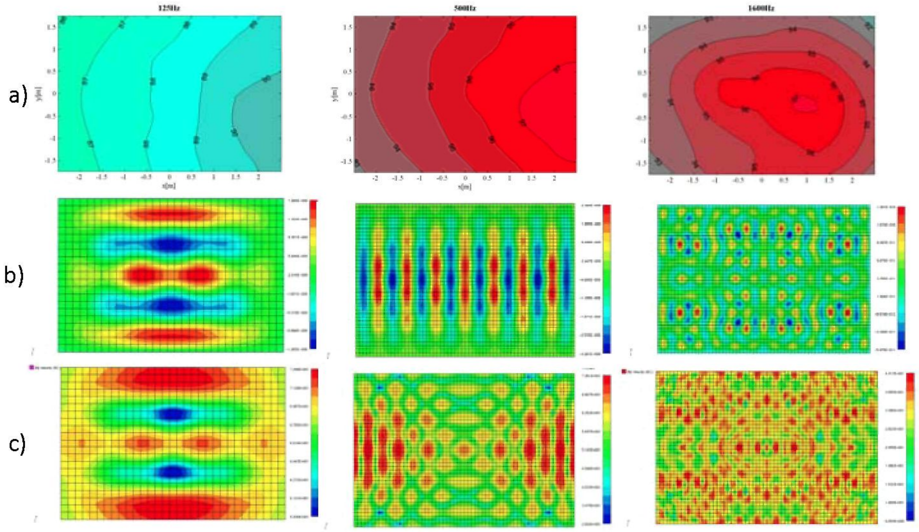


Figure 2 – a) incident pressure distribution, b) vibration of the façade, c) pressure behind the façade.

However, there is total symmetry in the simulated maps of the vibration of the façade and the interior acoustic pressure behind the façade. The corresponding symmetry of the acoustic field around the building leads to the conclusion that the transmission of a sound wave through a uniform wall, rigidly fixed in its shape, does not depend significantly on the spatial distribution of the sound pressure level on the surface.

4. EXPERIMENTAL STUDY

An intermediate measure of the precision experiment was conducted in order to test the influence of loudspeaker directivity on the measurement results of insulation using the global loudspeaker method in the ISO 140-5 standard. The experiment consisted of a series of measurements on the same façade, in which all factors remained constant except the speaker used as a sound source. Four sound sources with different directional characteristics were used. For the experimental design we followed the criteria in ISO 5725-3 [11].

The façade in the test measures 5.29 x 3.45 m. The lowest part of the façade, up to a height of 1m, consists of a multilayer panel. The rest is made up of single glass, 5 mm thick, mounted on a metallic structure.

Attempts have been made to ensure that the only variable factor between the different tests is the speaker used as a sound source, while the rest of the test factors are maintained constant. A mobile microphone for measuring the sound pressure level in the receiving room was used to ensure an analogous sampling of the sound field in the different measurements. To establish the repeatability of each test, three repetitions of the measurement were made with each of the sound sources. A total of five tests were conducted with three replications each. Sound sources numbers 1 to 3 were used in tests 1 to 3, respectively. Tests 4 and 5 were done with sound source number 4, with two different loudspeaker orientations; in test 4 one of the cones is aimed at the center of the façade, while in test 5 one of the cones is aimed at the external microphone.

Table 3 shows the repeatability standard deviation s_i, the overall mean of the experiment m and the intermediate precision standard deviation $s_{I(E)}$.

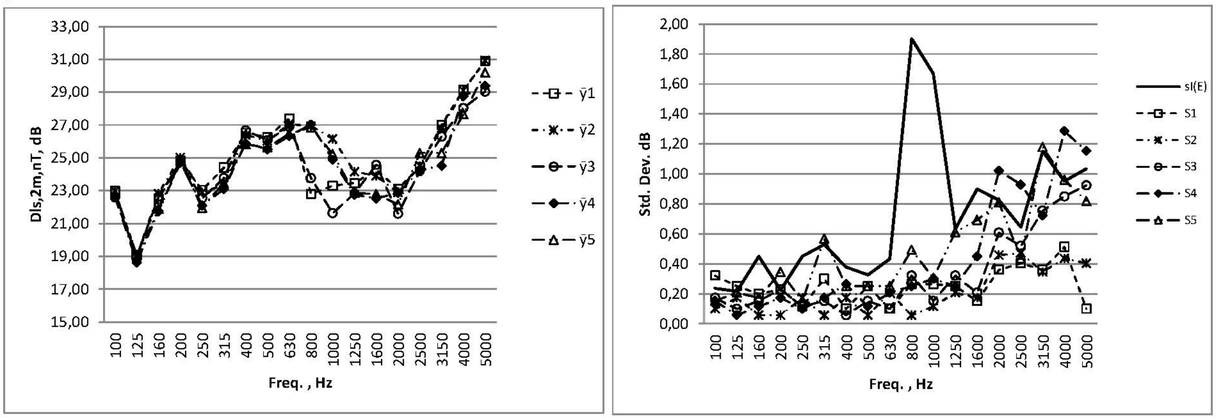
Figure 4a) represents the mean values for each test. We can see how for low frequencies no significant differences were obtained in the values of $D_{ls,2m,nT}$ in the different tests. The maximum disparity of results is found for the third octave bands centered between 800 and 1000 Hz. This disparity is not due to variations in the directivity of the sound sources used, but to the effect of ground reflection. For the third octave bands with center frequencies above 1250 Hz, the mean values of $D_{ls,2m,nT}$ obtained with the different sound sources differ more than 2 dB, with a maximum difference of 3.6 dB per band of 3150 Hz. These differences are probably attributable to the directivity of the loudspeakers.

Analyzing the values of standard deviations of repeatability (Figure 4 b), we note that, apart from the effect of reflections from the ground, the intermediate precision standard deviation, $s_{I(E)}$, increases for high frequencies, where the differences in directivity between the different speakers are more pronounced.

Table 3 - Summary of results

Freq.[Hz]		100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	$D_{ls,2m,nT,W}$
Test 1	s_1[dB]	0,32	0,25	0,20	0,23	0,12	0,30	0,10	0,25	0,10	0,26	0,26	0,25	0,15	0,36	0,40	0,36	0,51	0,10	0,58
Test 2	s_2[dB]	0,10	0,17	0,06	0,06	0,17	0,06	0,17	0,06	0,21	0,06	0,12	0,21	0,17	0,46	0,47	0,35	0,44	0,40	0,58
Test 3	s_3[dB]	0,17	0,10	0,15	0,23	0,12	0,15	0,06	0,15	0,10	0,32	0,15	0,32	0,21	0,61	0,52	0,75	0,85	0,92	0,00
Test 4	s_4[dB]	0,15	0,06	0,12	0,17	0,10	0,17	0,26	0,12	0,21	0,25	0,30	0,25	0,45	1,02	0,93	0,72	1,29	1,15	0,58
Test 5	s_5[dB]	0,15	0,21	0,17	0,35	0,15	0,57	0,25	0,25	0,25	0,49	0,31	0,61	0,69	0,81	0,44	1,18	0,96	0,82	0,00
Global	m[dB]	22,8	18,9	22,3	24,8	22,5	23,6	26,3	25,9	26,8	25,5	24,2	23,2	23,6	22,5	24,5	26,0	28,5	30,1	24,7
	$s_{I(E)}$ [dB]	0,24	0,22	0,45	0,23	0,45	0,53	0,38	0,33	0,43	1,90	1,67	0,63	0,90	0,83	0,64	1,15	0,95	1,03	0,59

In addition, we have compared the dispersions of the values of $L_{1,2m}$ and L_2 obtained in all tests. As expected, it was found that these dispersions obtained in the measurements are similar at low frequencies, while for medium and high frequencies, the dispersion of the values of $L_{1,2m}$ is considerably higher than that obtained for the values of L_2. This confirms that the effects of ground reflections and speaker directivity on the sound pressure level are more pronounced in the outdoor microphone position than in the sound field of the receiving room.



a) b)

Figure 4 - Results obtained. a) Mean values of $D_{ls,2m,nT}$, b) repeatability standard deviations

5. MEASUREMENT UNCERTAINTY

The Guide to the Expression of Uncertainty in Measurement, GUM [12] provides an analytical methodology on the evaluation and reporting of measurement uncertainty. According to this guide, the mathematical model of the measurement is:

$$D_{ls,2m,nT} = (L_{1,2m} + \delta(L_{1,2m})) - (L_2 + \delta(L_2)) + 10\lg((T + \delta(T))/T_0) \tag{2}$$

where $\delta(L_{1,2m})$, $\delta(L_2)$ and $\delta(T)$ represent the corrections associated with the input quantities that may contribute to the uncertainty of measurement of these quantities. In sound pressure level measurements, the main sources of uncertainty that are usually considered are those associated with the use of a sound level meter, and those due to the dispersion of the values measured at different points of the sound field, the latter usually being the most important in field measurements. In measurements according to the global loudspeaker method, the uncertainty component due to the directivity of the speaker must be added to these contributions.

It is difficult to make a general estimation of the uncertainty of the measurement of L 2 associated with loudspeaker directivity. However, taking into account the above, it is reasonable to assume that their contribution will be much smaller than the contribution of the sampling of the receiving room sound field, so it can be discarded.

If the directivity of the speaker is known, the directivity index data can be used to calculate the change in sound pressure levels in each third octave band in the position of the outdoor microphone, for all the possible angles of incidence. The minimum and maximum values of these differences for every frequency band can be taken as limits of error. Assuming a rectangular probability distribution, the component of uncertainty in the measurement of $L_{1,2m}$ due to the directivity of the speaker in each 1/3 octave band can be expressed as

$$u_{dir} = (L_{P\max} - L_{P\min}) / 2\sqrt{3} \tag{3}$$

This component should be added to the rest of the uncertainty components.

Table 4 - Uncertainty due to the directivity of loudspeaker for the sound sources considered.

Freq. [Hz]		100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
u_{dir} [dB]	*Source 1*	0,01	0,01	0,02	0,01	0,12	0,06	0,11	0,36	0,10	0,01	0,11	0,04	0,06	0,16	0,18	0,14	0,43	0,01
	Source 2	0,12	0,32	0,12	0,05	0,05	0,04	0,10	0,21	0,30	0,32	0,35	0,22	0,24	0,38	0,95	0,64	0,10	0,59
	Source 3	0,06	0,03	0,02	0,06	0,04	0,04	0,12	0,08	0,16	0,17	0,17	0,37	0,36	0,29	0,13	0,03	0,82	0,70
	Source 4	0,00	0,01	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,11	0,05	0,34	0,12	1,29	1,02	0,86	0,41	2,78

6. CONCLUSIONS

Speaker directivity significantly affects the results of measurements of sound insulation of façades when using the global loudspeaker method in standard ISO 140-5, and its uncertainty contribution must be taken into account when estimating the overall measurement uncertainty. For homogeneous walls, the effect of the directivity of the speaker is more significant in the outdoor microphone sound pressure levels than in the acoustic energy transmitted into the receiving room.

If the speaker directivity index values are known for all the possible directions of incidence to the external microphone, its contribution to the measurement uncertainty of $L_{1,2m}$ can be estimated by calculating the maximum variation of the sound pressure level for every 1/3 octave band, and assuming a rectangular probability distribution.

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